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ELECTRON BEAM WELDING OF THICK-WALLED COPPER CONTAINERS FOR NUCLEAR FUEL WASTE DISPOSAL - PHASE THREE A

Report No 85-100-K

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ABSTRACT

This report describes the results of Phase Three A of the copper electron beam welding project for the final closure of copper containers for nuclear fuel waste disposal. It has been demonstrated that oxygen-free copper electron beam welds of excellent quality can be made over a wide range of beam power and welding speed. Tension and side bend test specimens prepared from selected welded samples displayed satisfactory tensile strength and ductility. However, the test results show that suitable combinations of beam power and welding speed must be used to ensure a smooth defect-free weld surface.

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740681-144-461	823.241	July 31, 1985	85-100-K

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EXECUTIVE SUMMARY

ELECTRON BEAM WELDING OF THICK-WALLED COPPER CONTAINERS FOR NUCLEAR FUEL WASTE DISPOSAL PHASE THREE A

P.Y.Y. Maak
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As part of Ontario Hydro's technical assistance to the Canadian Nuclear Fuel Waste Management Program, the Welding Research Unit of the Metallurgical Research Department is investigating the feasibility of using electron beam welding for the final closure of copper containers for nuclear fuel waste disposal. The first, second and third phases have been completed. The results of Phase One and Phase Two have been reported in Reference 1 and Reference 2 respectively.

This report describes the results of Phase Three A. The present results show that square butt oxygen-free copper electron beam welds, displaying weld penetration in the range of 29.1 to 46.2 mm can be made at a wide range of beam power (13.5 to 42.0 kW) and welding speed (2.5 to 19.1 mm/sec). All the welds displayed excellent quality in the fusion zone, containing very little or no gas porosity and no large cavities. Tension and side bend tests were performed on selected welded samples. All the test specimens displayed satisfactory tensile strength and ductility.

However, the present results showed that suitable combinations of beam power and welding speed had to be used to produce copper EB welds free from any surface defects such as erratic metal overflow, undercuts and blow holes. The practical use of empirical equations for predicting weld penetration was discussed.

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To Mr. H.N. Issac
Manager
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ELECTRON BEAM WELDING OF THICK-WALLED COPPER CONTAINERS FOR NUCLEAR FUEL WASTE DISPOSAL PHASE THREE A

P.Y.Y. Maak

1.0 INTRODUCTION

As part of Ontario Hydro's technical assistance to the Canadian Nuclear Fuel Waste Management Program, the Welding Unit of the Metallurgical Research Department is developing an optimum electron beam (EB) welding procedure for the closure of thick-walled (~25 mm thick) copper containers for nuclear fuel waste disposal/3,4/. To date, the study has consisted of three phases.

In Phase One and Phase Two, it was demonstrated that square butt electron beam welds (depth of penetration >25 mm) could be made without preheat in both electrolytic tough-pitch (ETP) copper and oxygen-free (OF) copper plates using more than one combination of welding parameters. OF copper contains less dissolved oxygen in the base metal, and thus exhibits much better weld-ability than ETP copper. In comparison with the ETP copper welds, sound OF copper welds could be made using a much wider range of beam power and welding speed, without significant amounts of gas porosity in the fusion zone.

This report describes the results obtained in Phase Three A. Single pass, square butt electron beam welds were made in 25 mm thick OF copper plates, using a wide range of welding parameters to select the combination that provided welds with minimum gas porosity, no fusion zone cavities and a satisfactory weld surface finish. In Phase Three B, container closure was simulated by EB welding a small-scale ETP copper pipe mockup (wall thickness ≈25 mm), using selected combinations of welding parameters. Ultrasonic inspection studies were also carried out on the ETP copper closure weld. The results of Phase Three B will be described in a separate report/5/.

2.0 EXPERIMENTATION IN PHASE THREE A

Square butt welds were made in 25 mm thick oxygen-free copper workpieces, ~113 mm long and ~24 mm wide, with backing plates. The details of the welding trials are given in Table 1. All the welding trials were performed in the flat or 1G welding position. The welding parameters investigated were beam current, accelerating voltage and welding speed. All welded samples were examined visually, and cross-sections were prepared for metallographic examination. Hardness, bend and tension tests were performed on selected welded samples.

3.0 EXPERIMENTAL RESULTS

3.1 Metallographic Studies

The surface appearance and cross-sections of the oxygen-free copper welds are shown in Figures 1 to 6. The depth of penetration of these welds are given in Table 1.

3.1.1 Low Beam Power/Low Welding Speed Studies

Welds 34, 35, 44 and 45 were made at low beam power levels (13.5 to 20 kW) and low welding speed (2.5 to 5.9 mm/sec or 6 to 14 in/min). The measured penetration of these welds ranged from 29.1 to 33.0 mm. The surfaces of these welds were smooth, displaying no blow holes or erratic molten metal overflow (See Figures 5a, 5b, 5c and 5d). In general, they displayed a wide upper bead which became gradually narrower as the weld penetration increased (see Figures 1 and 2a).

Welds 42 and 43 were made at a higher beam power of 22.0 kW and at welding speeds of 7.6 mm/sec (18 in/min) and 5.9 mm/sec (16 in/min) respectively. Weld penetrations were 37.4 mm and 40.3 mm for welds 42 and 43. The fusion zones of these welds were parallel-sided, except near the weld surface (see Figures 2b and 2c). At the higher beam power of 22.0 kW, the weld surfaces displayed erratic metal overflow, blow holes and some undercutting (see Figures 5e and 5f).

The fusion zone of all welds examined contained very low levels of gas porosity. A small root cavity was found in weld 35 (see Figure 2a). Some small cavities were detected in the lower part of weld 43 (see Figure 2b).

The results also showed that low welding speed promoted lateral melting. Welds 34, 44 and 45, made at low welding speeds (2.5

to 3.4 mm/sec), displayed a wider fusion zone than the other welds. The deep penetration in these welds was obtained at the expense of high heat input (46.3 to 54.0 kJ/cm).

3.1.2 High Beam Power/High Welding Speed Studies

Welds 36, 37, 38, 39, 40 and 41 were made using high beam power (27.5 to 42.0 kW) and high welding speed (10.6 to 19.1 mm/sec or 25 to 45 in/min). In comparison with those welds made at low welding speed and beam power, the fusion zones of these welds were narrower and more parallel-sided (see Figures 1, 3 and 4). The weld penetration ranged from 35.4 to 46.2 mm (see Table 1). The present results showed that high beam power/high welding speed combinations promoted deep penetration and reduced the extent of lateral melting. Deep penetrating welds could then be made at relatively low heat inputs (18.8 to 28.4 kJ/cm). However, erratic metal overflow, blow holes, and undercutting were found on the surface of all these welds (see Figure 6). The high beam power in combination with the high welding speeds appeared to promote an excessive amount of surface defects.

3.1.3 Microstructure of the Oxygen-Free Copper Electron Beam Welds

Despite the variation in weld geometry with different combinations of beam power and welding speed, no significant difference in fusion zone grain structure was found.

The microstructures of welds 34, 35 and 38 are shown in Figures 7 and 8. The typical fusion zone consists of a narrow zone of small grains ($\leq$1 mm wide) surrounded by a wide zone of slightly larger grains. The grains in the fusion zone appear to merge nicely with grains in the heat-affected zone of the base metal. Many "ghost lines" were found in the fusion zones. Examination under optical microscope at 1000X magnification confirmed that these lines were merely an etching effect related to no distinguishable microstructure or oxides. They probably represent the flow lines of the molten metal during the solidification process.

3.2 Mechanical Testing

3.2.1 Hardness Tests

Vickers hardness tests were performed on a cross-section of weld 38. The fusion zone hardness ranged from 42 to 51

Vickers points and the base metal hardness ranged from 54 to 63 Vickers points. No significant hardness difference was found at various depths of weld 38.

3.2.2 Tension Tests

Three sample welds, made at distinctly different combinations of welding parameters, were selected for tension testing. Weld 34 was made at low welding speed (3.4 mm/s) and low beam power (15.8 kW). Weld 35 was made at an intermediate welding speed (5.9 mm/sec) and intermediate beam power (20.0 kW). Both welds displayed a slightly tapered fusion zone and a smooth weld surface. Weld 38 was made at a high welding speed (14.8 mm/sec) and high beam power (36.0 kW). This weld displayed a more parallel-sided fusion zone and a rough weld surface containing blowholes and erratic metal overflow.

Small Houndsfield transverse tension test specimens were machined from approximately the mid-sections of these welded samples. The test results are given in Table 2.

All three tension test specimens displayed satisfactory tensile strength and ductility, however, the specimen from weld 35 displayed a slightly lower tensile strength and ductility (weld 35 used an intermediate welding speed and beam power).

3.2.3 Side Bend Tests

Guided side bend specimens were prepared from the welds 34, 35, and 38. The test results were satisfactory (see Table 2), as no visible cracks were found in the bend specimens.

4.0 DISCUSSION

4.1 Weld Defects in the Fusion Zone

In Phase Two of the copper EB welding studies/2/ it was shown that high levels of dissolved gases such as oxygen in electrolytic tough-pitch (ETP) copper lead to a high level of gas porosity in the fusion zone. Sound ETP copper welds could only be made using a narrow range of welding parameters. In contrast, the dissolved oxygen content in the base metal of oxygen-free copper is always carefully controlled and kept at an extremely low level. The present study showed that OF copper electron beam welds, containing a very low level of gas porosity, could be made over a wide range of beam power (13.5 to 42 kW) and welding speed (2.5 to 19.1 mm/sec).

The Phase Two studies showed that extremely high welding speeds ($\geq$25.4 mm/sec) promoted the formation of large cavities in the fusion zone. The present results demonstrated that the formation of such cavities could be prevented by using welding speeds at or below 19.1 mm/sec (45 in/min).

In the present study, small root cavities were found in welds 35, 36, 37 and 43. These welds were made at power levels of 20.0 to 36.0 kW, and welding speeds of 5.9 to 12.7 mm/s. In the Phase Two studies, small root cavities were found in copper electron beam welds made at relatively low power levels (13.5 to 22.5 kW) and welding speeds (3.4 to 8.5 mm/sec). These results appear to indicate that root cavities may form when using a wide range of beam power (13.5 to 36.0 kW) and welding speeds (3.4 to 12.7 mm/s or 8.0 to 30 in/min). With the present weld joint designs/1/, however, root cavities are believed not to have a significant detrimental effect on the integrity of the joint since they would be deeply embedded in the integral backing of the container's top lid or the side wall.

No cracking or any other types of internal weld defects were observed in this investigation.

4.2 Surface Weld Defects

The present study showed that high beam power coupled with high welding speeds promoted erratic molten metal overflow, blow holes and undercutting on the surface of OF copper electron beam welds. Some large blow holes and undercuts were found to extend 3 to 4 mm below the weld surface, reducing the minimum corrosion thickness of the weld and providing potential areas for accelerated localized corrosion.

In contrast, combinations of relatively low beam power and low welding speed (ie, welding parameters in test 34, 35, 44 and 45) provided welds with a smooth weld surface. For future studies, the individual and collective effects of beam power and welding speed on the formation of surface defects should be investigated. Another possible area of investigation could be the use of a low power cosmetic pass over the main weld for the purpose of repairing surface defects.

4.3 Weld Geometry, Microstructure and Mechanical Properties

The present study showed that at low welding speeds (<3.4 mm/s), the fusion zone of the copper E.B. welds generally displayed a wide upper bead which tapered to a very narrow underbead. As the beam power and welding speed were increased, the fusion zone

of the welds became more parallel-sided. Overall, the fusion zones examined in this investigation were very narrow and displayed high depth-to-width ratios. Over the wide range of beam power and welding speeds studied here, no significant difference in fusion-zone grain structure was detected.

Transverse tension and side bend test specimens, prepared from welded samples displaying distinctly different weld geometry and weld surface appearance, exhibited satisfactory tensile strength and ductility. These results indicate that the small differences in weld geometry do not appear to have any significant effect on the mechanical properties of the OF copper electron beam welds.

4.4 Weld Penetration

4.4.1 Welding Parameters and Heat Input

For the final closure joint described in Reference 1, the preferred weld penetration is in the range of 30 to 35 mm. The heat input energy required for fabrication of the closure weld should be kept to a minimum to reduce weldment distortion and overheating of the contents of the copper container.

The present study showed that EB welds in oxygen-free copper could be made at extremely low heat input using high beam power and high welding speeds, which appeared to promote deep penetration (>30 mm) and reduced lateral melting. However, it was also shown that high beam power and high welding speed promoted weld surface defects such as blow holes and undercutting. Therefore, the highest tolerable beam power and welding speed that would produce a smooth weld surface without surface defects should be selected for the final closure welding of copper containers. Based on this acceptance criterion, the highest tolerable beam power and welding speed observed were 20.0 kW and 5.9 mm/sec (14 in/min), ie, the weld 35 parameters. In future studies, other combinations of beam power and welding speeds slightly above and below the test 35 parameters should be investigated.

4.4.2 Empirical Equations for Prediction of Welding Penetration

In the Phase One studies/1/, an empirical equation was developed for prediction of weld penetration, which had the basic form:

$$P_p = KE^a I^b \frac{1}{S^c} \qquad (1)$$

where P_p = predicted penetration (mm); K = material constant
E = accelerating voltage (kV); I = beam current (mA)
S = welding speed (mm/s)
a,b,c = coefficients for E, I, and S respectively.

By using the penetration data obtained in Phase Two, the values of K, a, b, c were determined and the resulting general equation for weld penetration was found to be:

$$P_p = 0.003 \frac{E^{1.58} I^{0.64}}{S^{0.42}} \qquad (2)$$

Predicted weld penetrations (P_p) and measured weld penetrations from photographs of the present test welds (P_m) are compared in Table 1. Equation (2) appears to overestimate the weld penetration in the power range of 13.5 to 20.0 kW. In this case, $P_m - P_p$ was found to range from -1.2 to -3.9 mm. In contrast, Equation (2) underestimated the weld penetration at high power levels, 22.0 to 42.0 kW, particularly at beam power levels at or greater than 36.0 kW. For these tests, $P_m - P_p$ was found to range from +2 to +6.0 mm.

It was observed by Johnson/6/ that the electron beam spot size changed with beam power, which determined the energy density of the electron beam, and was thus an important factor for controlling weld penetration. However, at the present time there is no accurate and reliable method to measure the spot size. Equation (2) was thus developed in Phase Two without taking into account the effects of changes of beam spot size on weld penetration. The relatively large discrepancies between the predicted and measured weld penetration may indicate that changes in beam spot size with beam power indeed have significant effects on the penetration characteristics of copper electron beam welds over the power range of 13.5 to 42.0 kW.

The present results suggest that in order to develop an empirical equation that can be used to predict weld penetration over a wide range of beam power, it is essential to determine the change in beam spot size with power and to evaluate the effect of beam spot size on weld penetration in copper electron beam welds. At this time, the difficulties of determining the beam spot size render the development of such a general equation impractical.

In electron beam welding, the beam power can be kept to within ±1/4% of the particular machine setting. In future studies, an empirical equation will be developed for prediction of weld penetration within a narrow range of beam power eg, ±3 kW of a selected power level. For a narrow range of beam power, changes in beam spot size with beam power should be small enough to have no significant effect on weld penetration. Such an empirical equation can thus be used for weld parameter quality control monitoring during the final closure welding of copper containers.

5.0 CONCLUSIONS

5.1 Square butt, single pass EB welds of adequate penetration (>30 mm) and good mechanical integrity can be made in OF copper using a wide range of beam power/welding speed combinations. No gross fusion zone defects, such as gas porosity, cavities or cracking are found in the welds, although small root cavities are often observed, which are considered inconsequential due to the container weld geometry.

5.2 Surface defects such as blow holes, deep undercutting and erratic metal overflow are promoted by high power/high welding speed combinations and appear to be the limiting factor in welding parameter selection. Optimum welding parameters appear to be a beam power of 20.0 kW and a welding speed of 5.9 mm/s (test No 35 parameters), although more study is required to determine the individual and combined effects of power and speed on surface defect formation.

5.3 In the range of beam power of 13.5 to 42.0 kW, the change of beam spot size with beam power appears to have a significant effect on the penetration characteristics of copper EB welds. A general empirical equation defined in Phase Two, which has not taken the effect of beam spot size into account, fails to predict the weld penetration with sufficient accuracy for the purposes of weld process monitoring. In order to predict weld penetration more accurately, empirical equations must be defined for a narrow range of beam power in which the change of beam spot size would be negligible.

ACKNOWLEDGEMENTS

The author wishes to thank J. Galloway and D. Galbraith for carrying out the metallographic examinations and mechanical testing. Appreciation is also extended to the Manufacturing Technology Centre at the National Research Council for their

support in performing the welding trials. The author also wishes to thank M.J. Tinkler and L.J. Hosaluk for their helpful comments in the preparation of this report.

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TABLE 1

DETAILS OF OXYGEN-FREE COPPER ELECTRON BEAM
WELDING TRIALS IN PHASE THREE A

TEST WELD NO	BEAM CURRENT (mA)	ACCELER-ATING VOLTAGE (kV)	WELDING SPEED		BEAM POWER kW	HEAT INPUT		WELD PENETRATION (mm)		
			mm/s	(in/min)		kJ/cm	(kJ/in)	MEASURED P_m	PREDICTED P_p	$P_m - P_p$
45	300	45	2.5	(6)	13.5	54.0	(137.1)	29.1	32.2	-3.1
34	350	45	3.4	(8)	15.8	46.3	(117.6)	30.0	31.2	-1.2
44	350	50	3.4	(8)	17.5	51.5	(130.8)	33.0	36.9	-3.9
35	400	50	5.9	(14)	20.0	33.9	(86.1)	30.0	31.8	-1.8
43	400	55	5.9	(14)	22.0	37.3	(94.7)	40.3	37.0	+3.3
42	400	55	7.6	(18)	22.0	28.9	(73.4)	37.4	33.3	+4.1
36	500	55	10.6	(25)	27.5	25.9	(67.8)	35.4	33.4	+2.0
37	600	60	12.7	(30)	36.0	28.3	(71.9)	44.8	39.9	+4.9
38	600	60	14.8	(35)	36.0	24.3	(61.7)	43.4	37.4	+6.0
39	600	60	19.1	(45)	36.0	18.8	(47.8)	37.0	33.6	+3.4
40	700	60	14.8	(35)	42.0	28.4	(72.1)	46.2	41.3	+4.9
41	700	60	19.1	(45)	42.0	22.0	(55.9)	42.3	37.1	+5.2

TABLE 2

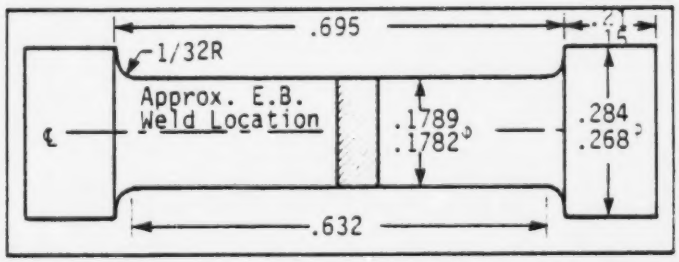
MECHANICAL TESTING RESULTS
TENSION TEST
(USING #12 HOUNDSFIELD**SPECIMENS)

Test Weld Number	Diameter mm	Area mm^2	Ult. Force KN	Ult. Stress M Pa	Elongation Percent	Failure Type	Failure Area
34	*4.54*	*16.18*	*3.19*	*197.2*	*36*	*ductile*	*weld*
35	*4.55*	*16.25*	*3.03*	*186.5*	*22*	*ductile*	*weld*
38	*4.54*	*16.18*	*3.30*	*204.0*	*40*	*ductile*	*weld*
A.T.D.*	*Transverse*			*153.6*	*46*	Percent in 2 inches	
	Axial			*163.0*	*48*		

* Average Tensile Data From /7/

** Dimensions of #12 Houndsfield Tensile Specimens

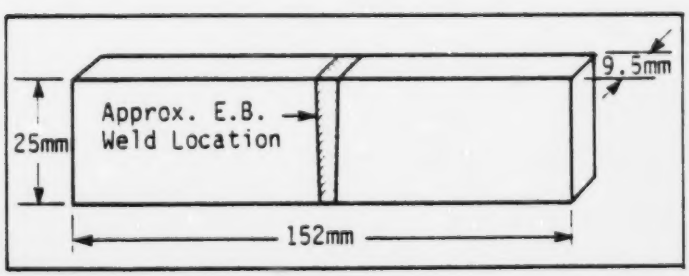
Note: Dimensions Are In Inches



GUIDED BEND TESTS (Dimensions of Test Samples***)

Test Weld Number	Type of Bend	Results
34	*side*	*satisfactory*
35	*side*	*satisfactory*
38	*side*	*satisfactory*

***



166908 RD

a) Test #45
(13.5kw, 2.5mm/s)

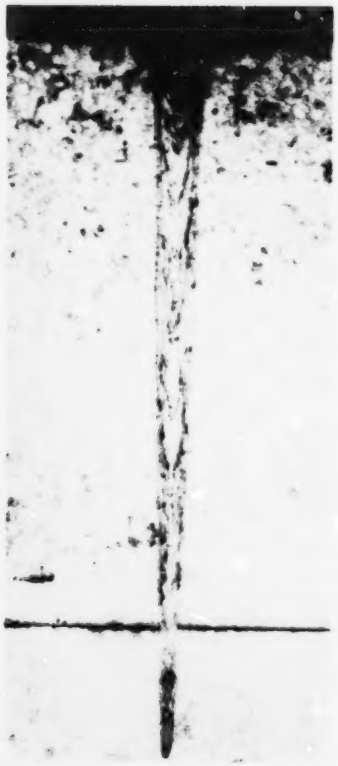
b) Test #34
(15.8kw, 3.4mm/s)

c) Test #44
(17.5kw, 3.4mm/s)

FIGURE 1

CROSS SECTIONS OF OXYGEN-FREE COPPER E.B. WELDS (3.5X MAG)

166900 RD



a) Test #35
(20.0kw, 5.9mm/s)

b) Test #43
(22.0kw, 5.9mm/s)

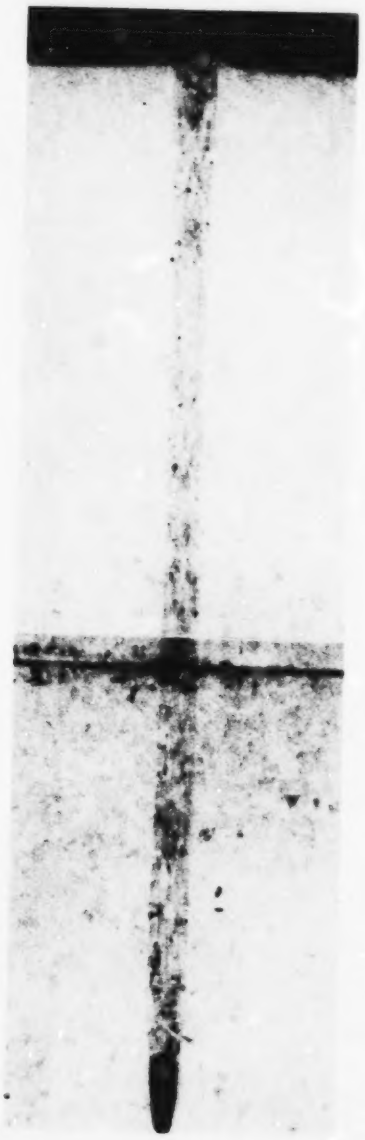
c) Test #42
(22.0kw, 7.6mm/s)

FIGURE 2

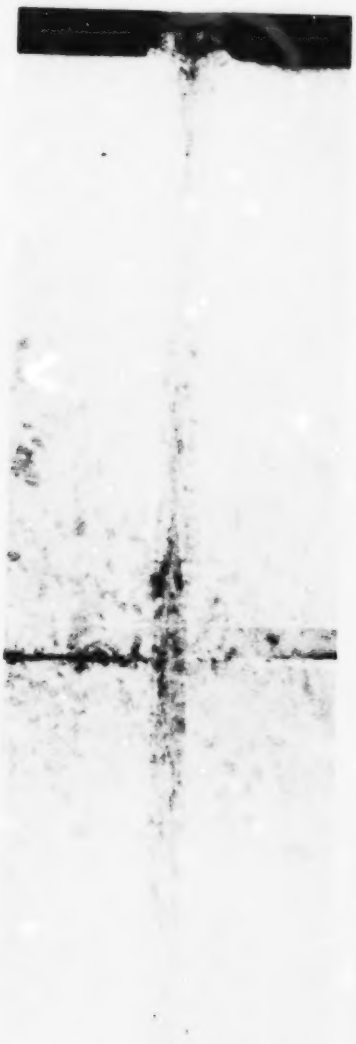
CROSS SECTIONS OF OXYGEN-FREE COPPER E.B. WELDS (3.5X MAG)

166901 RD

a) Test #36
(27.5kw, 10.6mm/s)



b) Test #37
(36.0kw, 12.7mm/s)

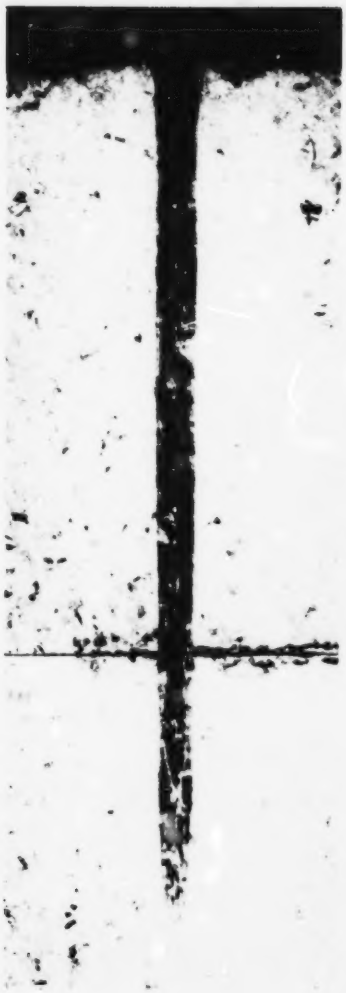


c) Test #38
(36.0kw, 14.8mm/s)

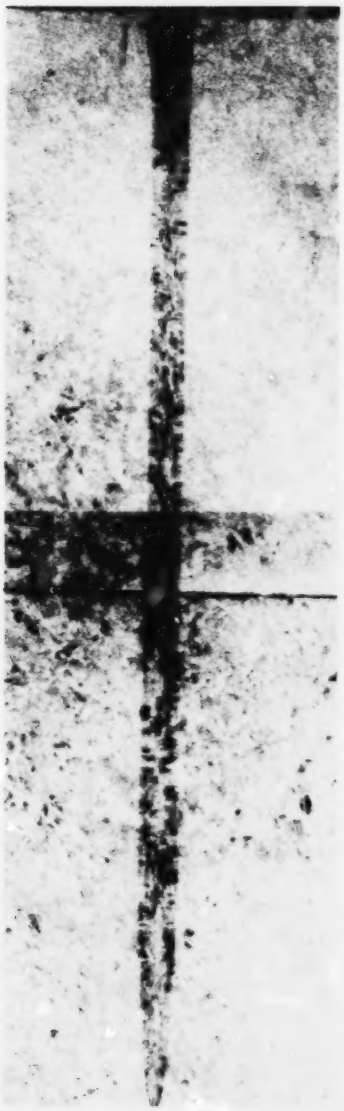
FIGURE 3

CROSS SECTIONS OF OXYGEN-FREE COPPER E.B. WELDS(3.5X MAG)

166902 RD



a) Test #39
(36.0kw, 19.1mm/s)



b) Test #40
(42.0kw, 14.8mm/s)

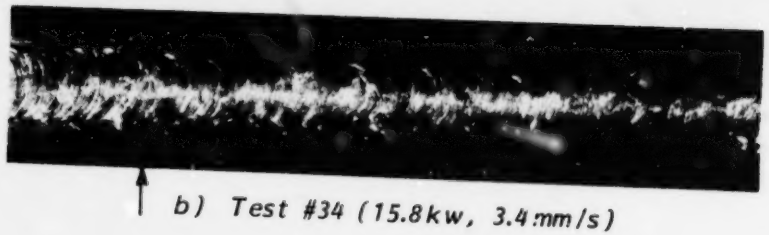
c) Test #41
(42.0kw, 19.1mm/s)

FIGURE 4

CROSS SECTIONS OF OXYGEN-FREE COPPER E.B. WELDS (3.5X MAG)

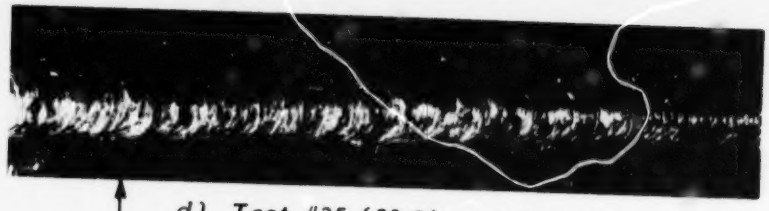
166903 RD

a) Test #45 (13.5kw, 2.5 mm/s)

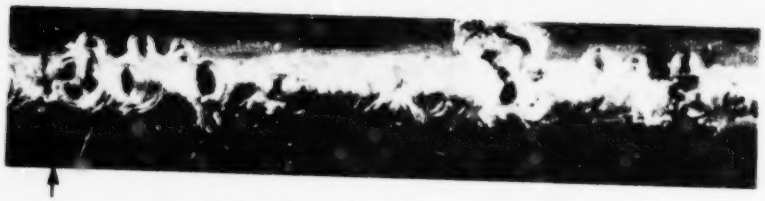


b) Test #34 (15.8kw, 3.4 mm/s)

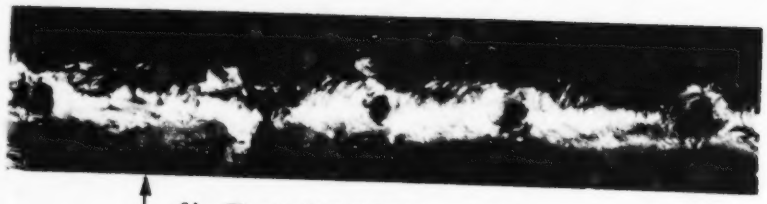
c) Test #44 (17.5kw, 3.4 mm/s)



d) Test #35 (20.0kw, 5.9 mm/s)



e) Test #43 (22.0kw, 5.9 mm/s)

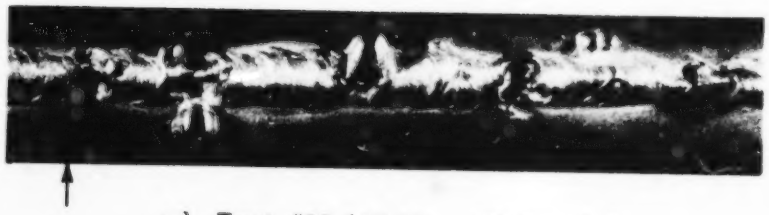


f) Test #42 (22.0kw, 7.6 mm/s)

FIGURE 5

SURFACE VIEW OF OXYGEN-FREE COPPER E.B. WELDS (2.0X MAG)
(ARROWS LOCATE THE AREA AT WHICH CROSS-SECTIONS WERE TAKEN)

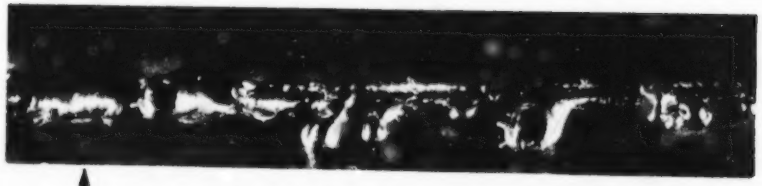
166904 RD



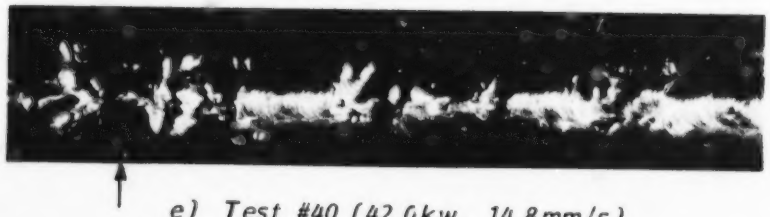
a) Test #36 (27.5kw, 10.6mm/s)

b) Test #37 (36.0kw, 12.7mm/s)

c) Test #38 (36.0kw, 14.8mm/s)



d) Test #39 (36.0kw, 19.1mm/s)



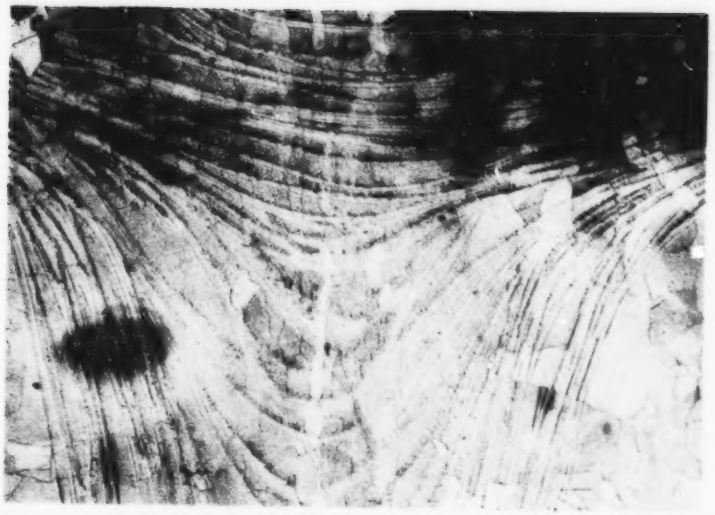
e) Test #40 (42.0kw, 14.8mm/s)

f) Test #41 (42.0kw, 19.1mm/s)

166905 RD

FIGURE 6

SURFACE VIEW OF OXYGEN-FREE COPPER E.B. WELDS (2.0X MAG)
(ARROWS LOCATE THE AREA AT WHICH CROSS SECTIONS WERE TAKEN)

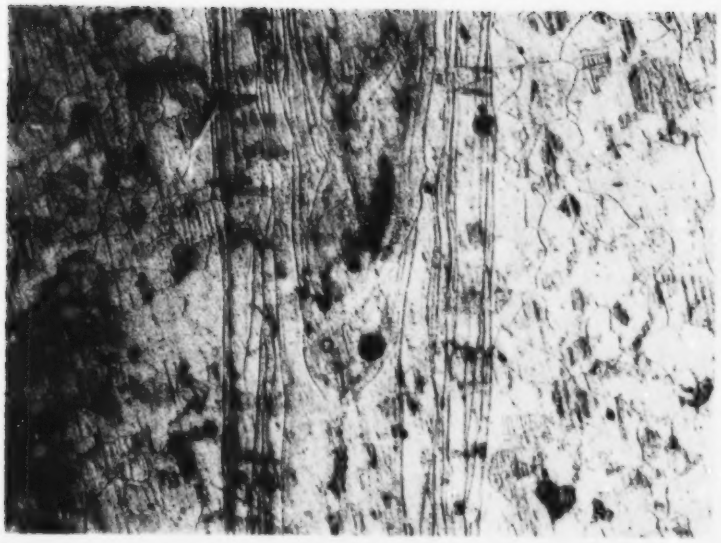


a) Near Weld Surface

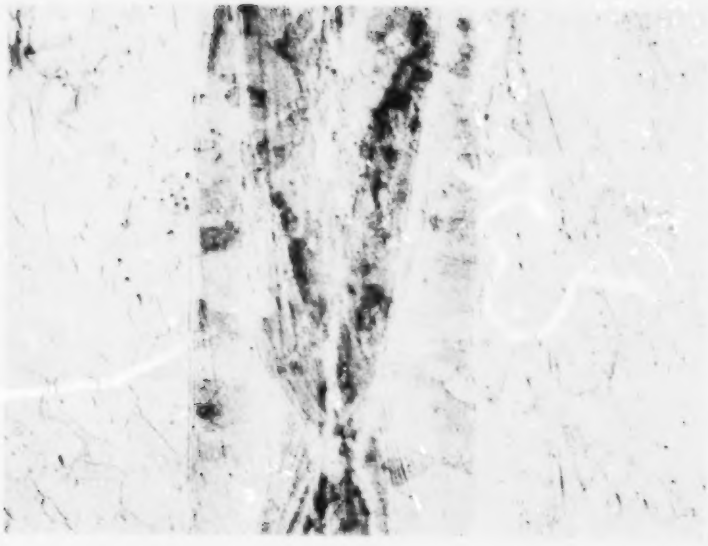
b) In Weld Mid-Section

FIGURE 7

MICROSTRUCTURE OF TEST WELD #34
(25X MAG)



a) Test Weld #35



b) Test Weld #38

FIGURE 8

MICROSTRUCTURE IN THE MID-SECTIONS OF
TEST WELD #35 AND #38 (25X MAG)

166907 RD